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Radiation Environment Predictions for Laboratory Tests

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14. ABSTRACT

Long-duration space environment exposure tests are performed to examine effects that might occur with materials exposed on external spacecraft surfaces. To properly simulate the orbital environment, information regarding the charged-particle environment is required. Once the orbital environment is known and tabulated, an energy deposition code is used to calculate energy dose depth profiles in selected materials for the electron and proton fluences during the mission. These are then simulated using a series of monoenergetic species that together sum up to a close approximation of the orbital dose profile.

The specific information needed for the environment in a particular orbit is the flux of the radiation as a function of energy. This information is generally available from upper-atmosphere models such as AE8 and AP8; however, these models are deficient at lower particle energies, resulting in under-prediction of the surface fluence. In this report, a method to predict a suitable radiation environment for laboratory simulations of a LEO orbit is described.

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1. Introduction

Long-duration space environment exposure tests are performed in the Space Radiation Effects chamber in The Aerospace Corporation Space Materials Laboratory to examine effects that might occur within materials exposed on external spacecraft surfaces. To properly simulate the orbital environment, information regarding the charged-particle environment is required. Once the orbital environment is known and tabulated, an energy deposition code is used to calculate energy dose depth profiles in selected materials for the electron and proton fluences during the mission. These are then simulated using a series of monoenergetic species that together sum up to a close approximation of the orbital dose profile. Predictions for a LEO orbital environment at 550 nmi and 98° inclination will be presented to illustrate the methodology.

2. Background

The specific information needed for the environment in a particular orbit is the fluence of the radiation as a function of energy. This information is generally available from upper-atmosphere models such as AE8 for trapped electrons, AP8 for trapped protons, and other models for plasma electrons and protons. The AE/AP models effectively model the trapped or higher energy portion of the total charged-particle environment. However, they are deficient at lower particle energies and are often simply extrapolated to lower energies using graphical techniques. The AE8 model does not include data for electron energies below 40 keV, resulting in under-prediction of the surface fluence. This under-prediction is significant for external surfaces on a spacecraft, such as thermal blankets, paints, radiators, or optical components. Similar problems occur with the proton spectrum, which is generally truncated at 100 keV.

Currently, there are no commonly agreed upon engineering models for the low-energy/high-flux particles. The AE/AP models are generally used for radiation calculations, even though the surface dose is almost certainly inaccurate. For electrons, the AE8 MAX is generally used, while for protons, the model used is AP8 MIN. The suffixes MAX and MIN refer to the relative solar activity (solar maximum or solar minimum) and are the worst-case conditions. The orbital lifetime then determines the total dose that the materials must tolerate.

3. Updated Models

With valuable contributions from the Space Sciences Department of the Space Science Applications Laboratory (SSAL) of The Aerospace Corporation, a suitable environment for laboratory simulation of the space environment has been developed. In a study completed in 1991 [Hardy et al., *J. Geophys. Res.*, (96), p5539, 1991], statistical auroral ovals for seven levels of Kp (a magnetic activity index) from 0 to 6+ were produced, using several years worth of data from three DMSP spacecraft. These spacecraft provided the precipitating auroral particle fluxes in the energy range of 30 eV to 20 keV. The data were binned by Kp, MLAT (magnetic latitude), and MLT (magnetic local time), and average particle energies and integral fluxes for each bin were calculated, extrapolating to higher energies assuming a Maxwellian electron distribution. The results were represented in each MLT sector by a simple functional form called the Epstein function [Booker et al., *J. Atmos. Terr. Phys.*, (39), p619, 1977].

In the SSAL Auroral Fluence Model, the orbital elements (MLT and MLAT) of a specific orbit are calculated for a period of time, such that all possible geomagnetic field conditions are experienced. The results of Hardy et al. [1991] are used to calculate the average energy and flux, folded through a probability distribution of Kp, for each bin. The average number flux in several energy bins between 30 eV and 20 keV in units of electrons/cm^2 s sr is then calculated, assuming a Maxwellian electron distribution, and multiplied by the time spent by the spacecraft in each bin to arrive at the total fluence calculations. These results are then merged with the AE-8 model to provide fluence results in the energy range from 30 eV to 6.5 MeV. The AE-8 model was developed using electron fluence data at energies above 40 keV. The results of the two models are combined and interpolated between 20 keV and 40 keV to provide a complete spectrum.

Estimates of the daily fluence of energetic particles for a circular orbit at 550 nmi with a 98° inclination are shown in Table 1 of the Appendix. The resultant fluences are supplied in energy bins used in previous fluence calculations. These are integral fluences, including the contributions from both the auroral zone and radiation belts. The second column is the integral fluence above the energy (E) in the first column, and the third column is the fluence in the energy band between E and the next higher energy. The integral fluences from column 2 (up to 1 MeV) are plotted in Figure 1.

Estimates of the daily fluence of energetic ions for circular orbit at 550 nmi with a 98° inclination were obtained in a similar manner using the SSAL Auroral Fluence Model. The orbital elements (MLT and MLAT) of a specific orbit are calculated for a period of time such that all possible geomagnetic field conditions are experienced. The results of a statistical auroral ion model developed by Hardy et al. [1991] are used to calculate the average ion energy and flux, folded through a probability distribution of Kp, for each bin. The average ion number flux in several energy bins between 30 eV and 70 keV in units of ions/cm^2 s sr is then calculated, assuming a Maxwellian ion distribution, and multiplied by the time spent by the spacecraft in each bin to arrive at the total fluence calculations. The AP8MIN model provides ion fluences above 100 keV. The results of the two models are merged to provide fluence results in the energy range from 30 eV to 350 MeV as shown in Table 2 of the

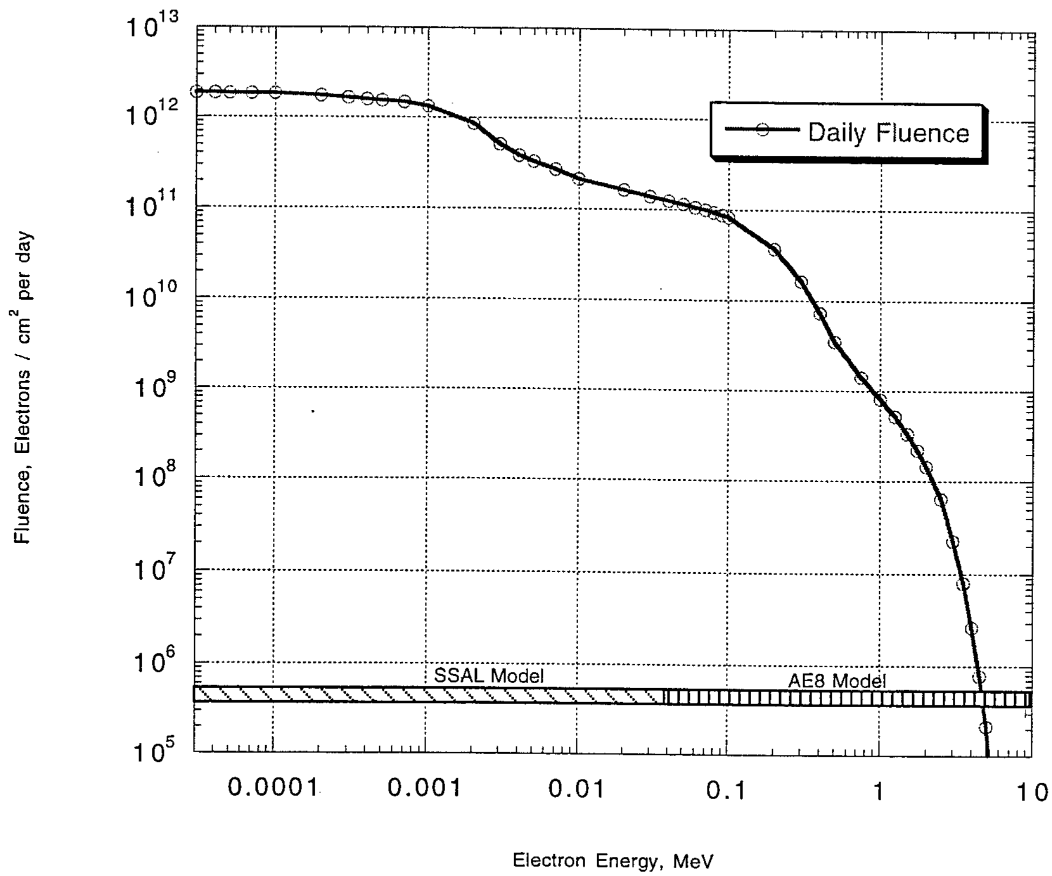

Figure 1. Daily electron prediction using the SSAL Auroral Model and AE8.

Appendix. These are integral ion fluences, including the contributions from both the auroral zone and radiation belts. The second column is the integral ion fluence above the energy (E) in the first column, and the third column is the ion fluence in the energy band between E and the next higher energy. The integral ion fluences from column 2 are plotted in Figure 2.

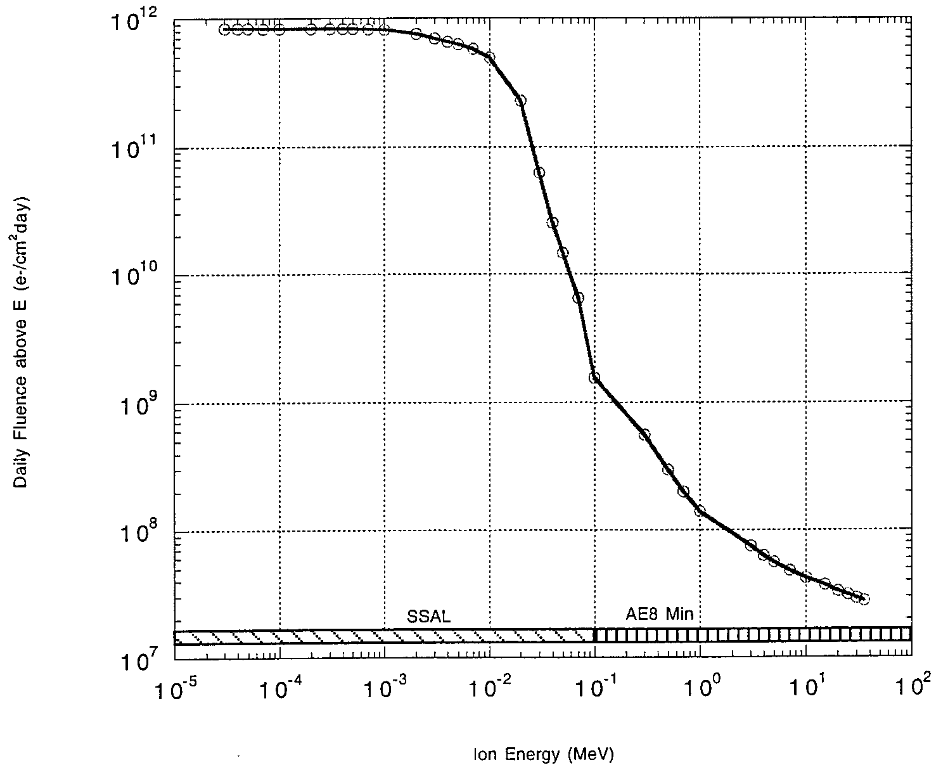

Figure 2. Daily ion fluence predictions using the SSAL Auroral Model and AE8Min.

4. Dose Predictions

The updated radiation environment predictions are used to calculate the absorbed dose from electrons using Tiger-P (part of the program Integrated Tiger Series v 3.0). Results for the electron dose-depth curve for Z93P, a white thermal control paint, are shown in Figure 3. This represents the expected dose to be accumulated by this material in the 550 nmi orbit for a duration of 15 years. The simulation of this exposure in the laboratory is accomplished by using a series of exposures at selected electron energies, the sum of which will closely match the orbital depth-dose curve. Figure 4 shows the predicted depth-dose curves for 5, 10, 20, 30, 50, and 100 keV exposures. The fluence at each level is selected so that the sum of the exposures matches the on-orbit curve, which is reproduced for comparison. The same depth-dose profile data is re-plotted for the outer one mil of thickness in Figure 5.

A similar approach is used for the proton simulation. The code used for the proton dose-depth profile is ProTran 1.02, a code developed by The Aerospace Corporation.* Figure 6 shows the predicted proton on-orbit depth-dose curve for a 10-year orbital exposure. The predictions for the simulation are shown in Figure 7.

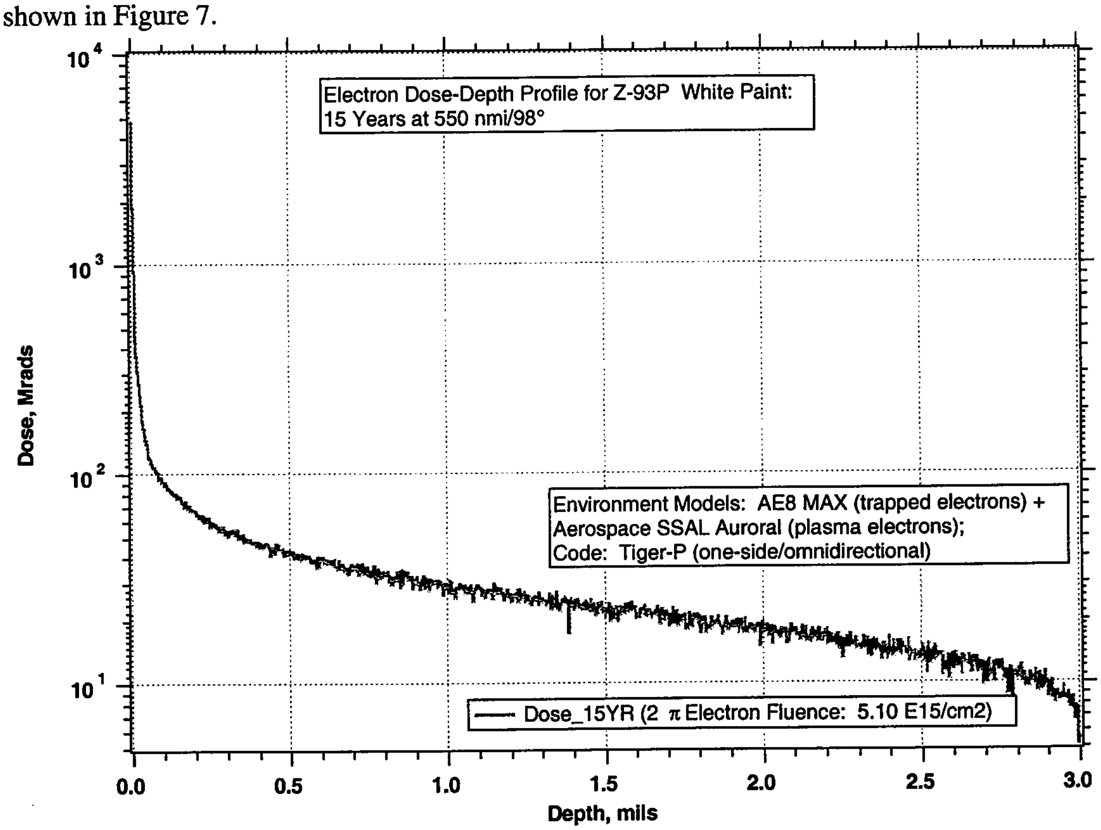

Figure 3. Predicted depth-dose profile for Z93P for 550 nmi/98° inclination orbit.

* J. M. Coggi, "A Proton Energy Deposition Computer Code for Materials in the Spacecraft Environment," ATM 95(5935-15)-3, The Aerospace Corporation, (10 May 1995).

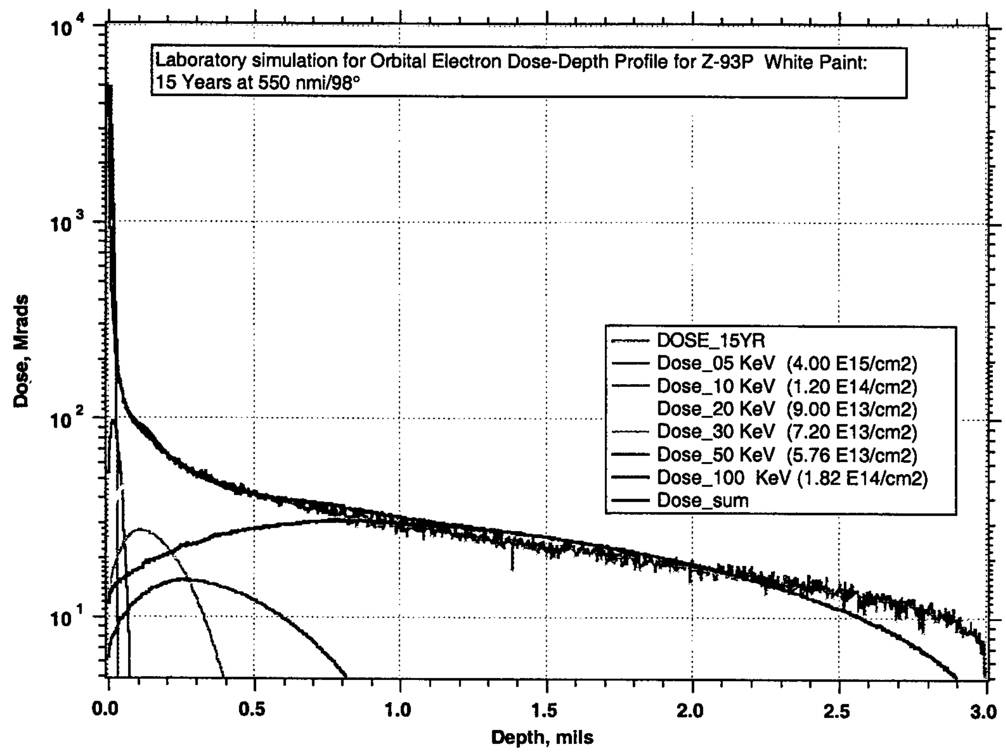

Figure 4. Predicted depth-dose profiles to simulate a 550 nmi/98° inclination orbit.

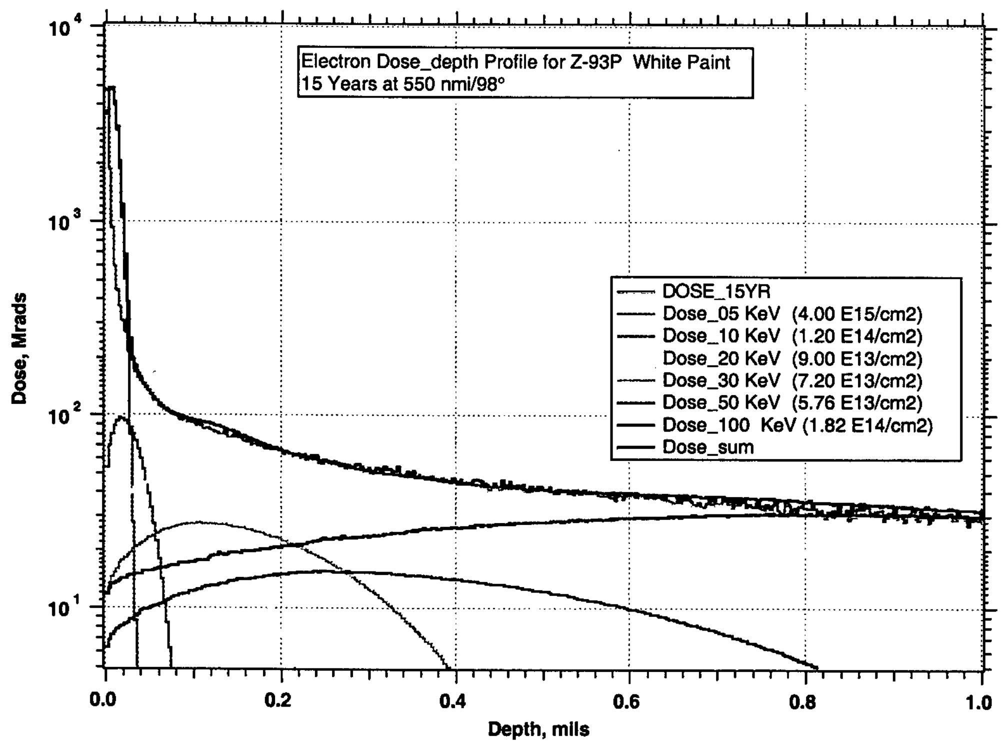

Figure 5. Predicted depth-dose profiles to one-mil thickness for a 550 nmi/98° inclination orbit.

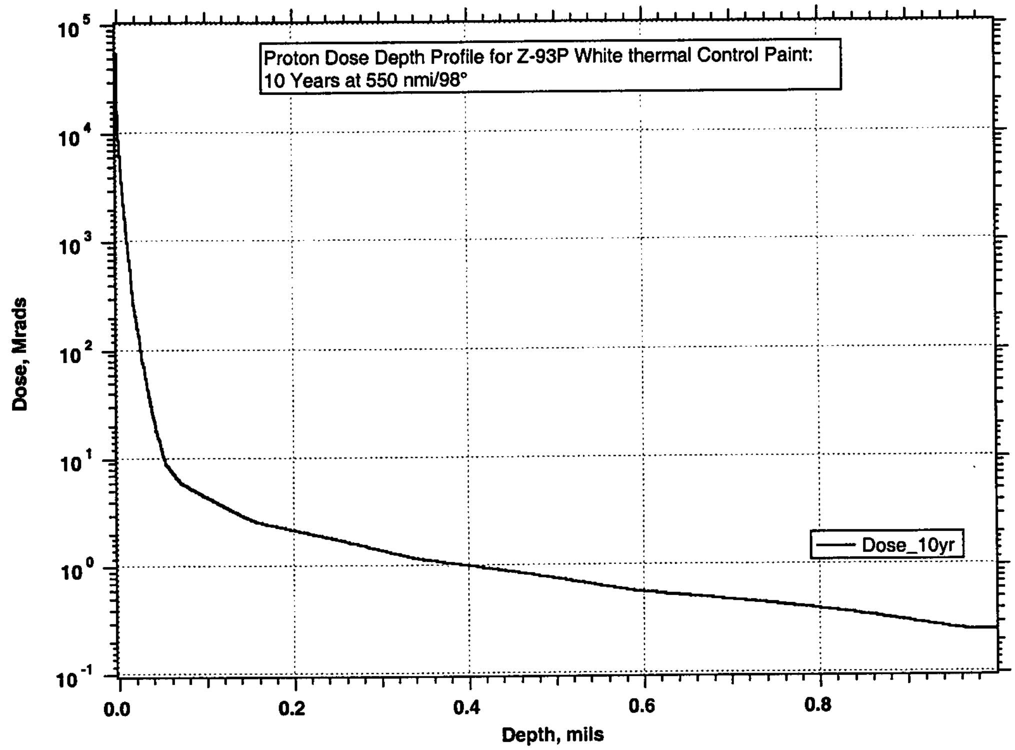

Figure 6. Predicted proton depth-dose profiles for a 550 nmi/98° inclination orbit.

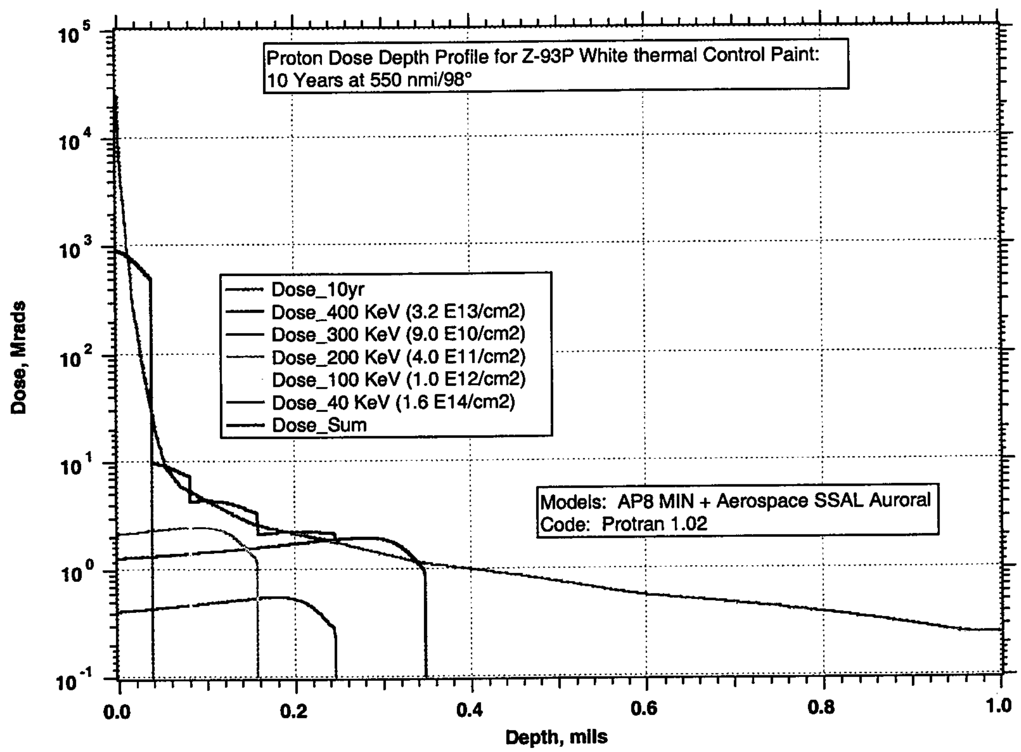

Figure 7. Predicted proton depth-dose profiles for a 550 nmi/98° inclination orbit.

5. Discussion

Dose profiles for a material are no better than the environment model used to generate them. The accuracy of the models is within an order of magnitude, but certainly not within a factor of 2. Additional errors can be introduced by the code, depending on how it handles geometry, backscatter, secondary-particle emission, and Bremsstrahlung. Material parameters such as density and composition are also approximations, especially for non-homogeneous materials. Normalization of a one-particle profile to an orbital particle fluence can also be an issue. In this work, the orbital profiles were calculated for a one-sided omni-directional exposure having a cosine distribution. Other geometries are possible, including normal and isotropic impingement. The model fluence, which is usually given for a 4π exposure, was halved to normalize the one-particle curve to one day. This represents a daily one-sided 2π omni-directional exposure. Multiplication by the appropriate number of days gives the desired orbital profile.

Appendix—Daily Electron and Ion Fluences

Table 1. Daily Electron Fluences for 550 nmi Circular, 98° Inclination

Ion Energy (MeV)	Daily Fluence Above E (e^-/cm^2 day)	Daily Fluence $E_1 - E_2$ (e^-/cm^2 day)
3.00e-05	1.86e+12	5.32e+09
4.00e-05	1.86e+12	2.31e+09
5.00e-05	1.85e+12	6.27e+09
7.00e-05	1.85e+12	1.38e+10
1.00e-04	1.83e+12	8.59e+10
2.00e-04	1.75e+12	9.67e+10
3.00e-04	1.65e+12	6.10e+10
4.00e-04	1.59e+12	4.18e+10
5.00e-04	1.55e+12	8.11e+10
7.00e-04	1.47e+12	1.30e+11
1.00e-03	1.34e+12	4.71e+11
2.00e-03	8.64e+11	3.56e+11
3.00e-03	5.09e+11	1.23e+11
4.00e-03	3.85e+11	5.36e+10
5.00e-03	3.32e+11	6.21e+10
7.00e-03	2.70e+11	5.75e+10
1.00e-02	2.12e+11	7.08e+10
4.00e-02	1.24e+11	2.27e+10
7.00e-02	1.01e+11	1.82e+10
1.00e-01	8.31e+10	4.55e+10
2.00e-01	3.76e+10	2.10e+10
3.00e-01	1.66e+10	9.27e+09
4.00e-01	7.30e+09	3.74e+09
5.00e-01	3.57e+09	2.14e+09
7.50e-01	1.43e+09	6.25e+08
1.00e+00	8.06e+08	2.90e+08
1.25e+00	5.16e+08	1.83e+08
1.50e+00	3.33e+08	1.15e+08
1.75e+00	2.19e+08	7.49e+07
2.00e+00	1.44e+08	7.92e+07
2.50e+00	6.43e+07	4.18e+07
3.00e+00	2.25e+07	1.45e+07
3.50e+00	8.01e+06	5.37e+06
4.00e+00	2.64e+06	1.86e+06
4.50e+00	7.77e+05	5.64e+00
5.00e+00	2.13e+05	2.05e+05
6.00e+00	7.98e+03	7.98e+03
7.00e+00	0.00e+00	0.00e+00

Table 2. Daily Ion Fluences for 550 nmi Circular, 98° Inclination

Ion Energy (MeV)	Daily Fluence Above E (e-/cm^2 day)	Daily Fluence E_1 - E_2 (e-/cm^2 day)
3.00e-05	8.29e+11	3.83e+07
4.00e-05	8.29e+11	1.89e+07
5.00e-05	8.29e+11	5.59e+07
7.00e-05	8.28e+11	1.37e+08
1.00e-04	8.28e+11	1.14e+09
2.00e-04	8.27e+11	1.66e+09
3.00e-04	8.26e+11	1.54e+09
4.00e-04	8.24e+11	1.44e+09
5.00e-04	8.23e+11	3.89e+09
7.00e-04	8.19e+11	8.57e+09
1.00e-03	8.10e+11	5.39e+10
2.00e-03	7.56e+11	6.17e+10
3.00e-03	6.94e+11	4.01e+10
4.00e-03	6.54e+11	2.79e+10
5.00e-03	6.26e+11	5.37e+10
7.00e-03	5.73e+11	8.33e+10
1.00e-02	4.89e+11	2.62e+11
2.00e-02	2.28e+11	1.65e+11
3.00e-02	6.24e+10	3.71e+10
4.00e-02	2.54e+10	1.08e+10
5.00e-02	1.46e+10	8.10e+09
7.00e-02	6.46e+09	4.92e+09
1.00e-01	1.55e+09	9.86e+08
3.00e-01	5.59e+08	2.62e+08
5.00e-01	2.97e+08	9.71e+07
7.00e-01	2.00e+08	5.97e+07
1.00e+00	1.40e+08	6.57e+07
3.00e+00	7.48e+07	1.22e+07
4.00e+00	6.26e+07	7.07e+06
5.00e+00	5.55e+07	7.45e+06
7.00e+00	4.81e+07	6.16e+06
1.00e+01	4.19e+07	5.00e+06
1.50e+01	3.69e+07	3.93e+06
2.00e+01	3.30e+07	2.03e+06
2.50e+01	3.09e+07	1.85e+06
3.00e+01	2.91e+07	1.39e+06
3.50e+01	2.77e+07	1.31e+06

LABORATORY OPERATIONS

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